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Suitability mapping framework for solar photovoltaic pumps for smallholder farmers in sub-Saharan Africa

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ABSTRACT

As solar panels become more affordable, solar photovoltaic (PV) pumps have been identified as a high potential water-lifting technology to meet the growing irrigation demand in sub-Saharan Africa (SSA). However, little is known about the geo-spatial potential of solar-based PV pumping for irrigation taking into account not only solar radiation but also the availability of water resources and linkage to markets. This study developed a suitability framework using multi-criteria analysis in an open source geographic information system (GIS) environment and tested it in the case of Ethiopia. The accessibility of water resources was the driving factor for different scenarios. Suitability results following the groundwater scenarios showed good agreement with the available referenced well depth data. Comparing the suitability maps with available land use data showed that on average 9% (96 10^3 ha) of Ethiopian irrigated and 18% (3,739 10^3 ha) of rainfed land would be suitable for solar PV pump irrigation. Furthermore, small solar PV pumps could be an alternative water-lifting technology for 11% of the current and future small motorized hydrocarbon fuel pumps on smallholder farms (2,166 10^3 ha). Depending on the technical pump capacity, between 155 10^3 ha and 204 10^3 ha of land would be suitable for solar PV pumps and provide smallholder farmers with the option to either pump from small reservoirs or shallow groundwater. With the ongoing interest in development for smallholder irrigation, the application of this model will help to upscale solar PV pumps for smallholder farmers in SSA as a climate-smart technology in an integrated manner.

1. Introduction

Irrigation is one of the key pathways for smallholder farmers to build resilience towards climate change (Alemayehu & Bewket, 2017). The increasing variability of rainfall and its effect on rainfed agricultural productivity in sub-Saharan Africa (SSA) has led to several studies attempting to estimate the availability and/or sustainable use of surface water and groundwater resources in irrigation (Altchenko & Villholth, 2015; Ashton, 2002; MacDonald, Bonsor, Dochartaigh, & Taylor, 2012; Pavelic, Smakhtin, Favreau, & Villholth, 2012; Xie, You, Wielgosz, & Ringler, 2014; You et al., 2011). Surface water and groundwater resources are highly variable throughout SSA and the latest climate scenarios suggest that variability and uncertainty will continue to increase (Gan et al., 2016; Vörösmarty, Ellen, Green, & Revenga, 2005). According to Arnell et al. (2016), under the A1b emission scenario, 127 million people in SSA will be exposed to a decrease in water resources whereas only 28 million will have access to increased water resources. Hence, with the increasing demand for resilient agricultural solutions in the context of food security and the promotion of irrigation throughout SSA, irrigation technologies are an essential component of climate-smart agriculture. Climate-smart agriculture is defined as technologies that ensure sustainable increases in productivity and income, increased climate adaptation and reduced greenhouse gas emissions below "business as usual" (FAO, 2013).

In SSA, a wide variety of manual (e.g. treadle pumps, rope and washer and other hand pumps) and motorized lifting technologies (e.g. petrol and diesel pumps) have been tested (Kamwamba-Mtethiwa, Weatherhead, & Knox, 2016 and references therein; Schmitter et al., 2016). While the adoption of manual water-lifting technologies remains rather site specific, the use of fuel-based motorized pumps has risen exponentially over the past decade in SSA (Giordano & de Fraiture, 2014; Namara, Hope, Sarpong, De Fraiture, & Owusu, 2014).

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Furthermore, combining surface water and groundwater, the use of motorized pumps could increase small-scale irrigable land by 30 million hectares (Mha) benefiting 180 million people and resulting in an annual net revenue of USD 22 billion (Xie et al., 2014). However, the access to hydrocarbon fuel remains a challenge in several SSA countries (Amjath-Babu, Krupnik, Kaechele, Aravindakshan, & Sietz, 2016). Additionally, the use of hydrocarbon energized motorized pumps would not fulfil the climate-smart criteria of reducing emissions in agriculture. Furthermore, rural electrification is particularly poorly developed in SSA, which significantly reduces the potential of electricity-based pumps as an alternative to hydrocarbon pumps, unlike for example, smallholder farming in India (Amjath-Babu et al., 2016).

As solar panels become more affordable, solar photovoltaic (PV) technologies, with their low carbon footprint, have been identified as high potential solutions for rural electrification as well as water extraction for both domestic and irrigation purposes in SSA (Chandel, Nagaraju Naik, & Chandel, 2015; Jäger-Waldau, 2017; Mohammed Wazed, Hughes, O'Connor, & Kaiser Calautit, 2018; Muhsen, Khatib, & Nagi, 2017). As such, solar PV pumps for smallholder farmers have become an emerging technology in SSA (Burney, Woltering, Burke, Naylor, & Pasternak, 2010; Burney & Naylor, 2012; Kamwamba-Mtethiwa et al., 2016; Mohammed Wazed et al., 2018). A review by Chandel et al. (2015) shows that solar PV-based pumping can be more economically viable in urban and rural areas compared to both hydrocarbon energized and electrical pumps. The continuous improvement of the technology and the reduction in capital investment required, which remains a challenge in SSA, could make solar PV pumps an affordable alternative to hydrocarbon fuel and electrical pumps in smallholder irrigation (Chandel et al., 2015; Mohammed Wazed et al., 2018). However, the economic viability is highly dependent on water supply meeting the water demand (Muhsen et al., 2017; Odeh, Yohanis, & Norton, 2006).

Geographic information system (GIS)-based mapping has been used effectively to assess suitability and feasibility of renewable energy, water resources or specific crop systems (Akyol, Kaya, & Alkan, 2016; Palmas, Abis, von Haaren, & Lovett, 2012; Szabó, Bódis, Huld, & Moner-Girona, 2011, 2013; Venkatesan, Krishnaveni, Karunakaran, & Ravikumar, 2010; Worqlul, Collick, Rossiter, Langan, & Steenhuis, 2015; Worqlul et al., 2017; Yalcin & Kilic Gul, 2017). Multi-criteria decision making (MCDM), first developed by Saaty (1977), and a wide range of related methodologies offer a variety of techniques and practices to uncover and integrate decision makers' preferences into "real-world" GIS-based planning and management solutions (Ascough et al., 2002). Various applications of MCDM have been used to assess the potential of agricultural water management strategies for smallholder farmers. For example, Worqlul et al. (2017) used MCDM in Ethiopia to identify 7.5% to 12.4% of potential suitable irrigable land that could be irrigated using groundwater resources. The Food and Agriculture Organization of the United Nations (FAO) (FAO, 2012) has developed and used a multi-criteria GIS framework to map the potential for investments in agricultural water management in SSA.

The existing suitability analysis methodologies can be adapted for the suitability analysis of solar PV pumps for smallholder irrigation. However, a multi-criteria GIS-based platform has not yet been developed to assess the suitability of solar-based PV pumps for smallholder irrigation (i.e., < 1 ha) in Africa taking into account available water resources, despite the availability of solar irradiation estimates such as those from the European Commission, Joint Research Centre (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php) (Huld, 2017; Huld, Müller, & Gambardella, 2012). In India, remote sensing has been used to quantify solar irradiation and then combined with data on elevation and land use to map suitability for concentrated solar power and centralized solar PV systems (Mahtta, Joshi, & Jindal, 2014). The gap in suitability maps for solar-based PV pump irrigation suggests the need to develop and test such methodologies in Africa. Therefore, this study sought to (i) develop a GIS-based methodology utilizing open source software to evaluate the potential of solar-based PV pumps using shallow groundwater and surface water, and (ii) test the performance of the model in Ethiopia. Identifying suitable locations for solar-based irrigation is particularly urgent as various investors consider out-scaling the systems. The suitability mapping can be integrated into planning for overall sustainable irrigation development in SSA, and more specifically, to evaluate possible investments in solar pump business models.

2. Materials and methods

2.1. Study site

Ethiopia was chosen as the pilot case to develop the multi-criteria model given the wide range of altitude (−125 meters above sea level [masl] to 4,550 masl) and corresponding diversity of agro-ecological zones (Fig. 1). The agro-ecological zones are characterized by differences in topography, solar irradiation, rainfall, geology, and hence soil types as well as land uses. Hence, the complexity and variety of these agro-ecological zones provide a great opportunity to develop and test a multi-criteria environment.

Approximately 85% of the population and 75% of livestock live in rural Ethiopia covering approximately 76.3 Mha (45% of the total land area) (Dejene, 2003; Leta & Mesele, 2014). Many of the highly populated towns are located in the wet and moist zones of the mid-highlands. Therefore, road infrastructure is dominant in the mid-highland agro-ecology. While the majority of agricultural land is purely rainfed, 1.3% is estimated to be under smallholder irrigation (Sheahan & Barrett, 2017). Recently, the Ethiopian Agricultural Transformation Agency (ATA) has estimated that approximately 11 Mha would be suitable for irrigation of which 48% could be irrigated using groundwater (Agricultural Transformation Agency (ATA), 2016). Moreover, Ethiopia places high priority on irrigation development within its Transformation Agenda to sustainably intensify agriculture and improve food security.

2.2. Data and pre-processing

Data selection focused on biophysical parameters as well as two indicators representing market access. The latter is considered a critical factor providing economic incentives for investment in irrigation development. The input maps selected for the analysis were based on their accessibility (i.e., preferably open source), resolution and relevance for the development of the multi-criteria tool. Five main categories of data were identified to assess the potential of solar PV pumps for surface water and shallow groundwater-based irrigation: (i) topography and soil suitability, (ii) rainfall, (iii) surface water and groundwater resources, (iv) land use and protected areas, and (v) road infrastructure, towns and population. The Geographic Resources Analysis Support System (GRASS) GIS modules (*r.sun, r.reclass*, and *r.mapcalc*) were used to pre-process the input data (Table 1). The vector data layers including road, river, land cover and national park were converted to raster data.

The DEM Shuttle Radar Topography Mission (SRTM) (30 m resolution) was used to derive the elevation class, aspect and slope information with the same resolution. The annual rainfall data (resolution 900 m) was obtained from WorldClim (WorldClim, 2005). The agro-ecological zones were derived using annual rainfall and the elevation classes based on the criteria defined by Hurni (1998) (Fig. 1).

As the main objective of the study was to assess the feasibility of solar PV pumps rather than the suitability of irrigable land, the soil suitability input was restricted to the depth of the soil profile by using the depth to bedrock (resolution 250 m). Soil suitability for irrigated agriculture is complex and would entail a full assessment of the various soil types. Furthermore, no specific crop was chosen to prevent constraining the model to a specific crop water demand and hence application of irrigation.

Irradiation maps from the Photovoltaic Geographic Information

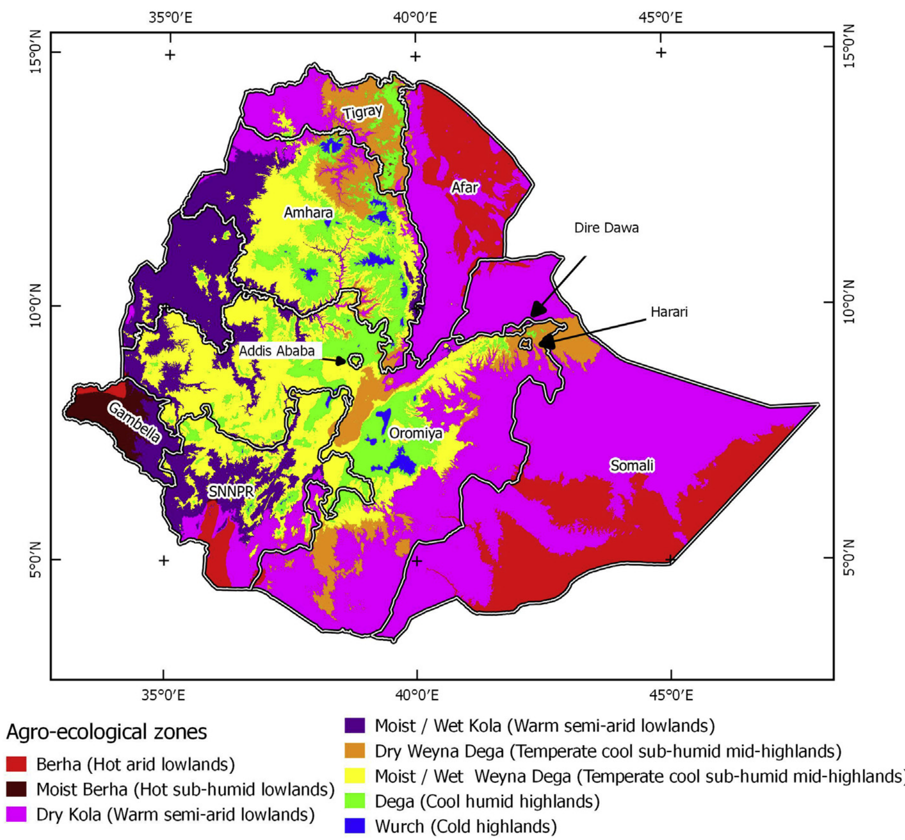

Fig. 1. Agro-ecological zones of Ethiopia based on the Digital Elevation Model (DEM) (30 m resolution) and WorldClim (2005). Modified categories according to Hurni (1998). ***Note***: SNNPR - Southern Nations, Nationalities, and People's Region.

System (PVGIS) with a coarse resolution of 2,000 m were obtained (see Table 1). However, the data is too coarse to consider the slope and aspect conditions of smallholder farms (i.e., 1 ha and smaller) in the Ethiopian highlands and mid-highlands. Hence, elevation, aspect and slope information was used to generate a moderate resolution (i.e., 30 m) irradiation map using the *r.sun* model of GRASS (Krcho, 1990) following the procedures established by Huld, Gottschalg, Beyer, and Topič (2010) and Huld (2017). The *r.sun* model allows to compute solar incidence angle and/or irradiation raster maps. The shadowing effect due to the topography was incorporated. Calculating the annual irradiation using a single day value introduces a high uncertainty given the seasonal variation. On the other hand, calculating single day irradiation values for 365 days is computationally demanding. Therefore, taking into account the differences in length of sunshine hours throughout the four seasons, the irradiation was calculated at 0.5 h intervals for day 1, 45, 90, 135, 180, 225, 270, and 315 of the year. The days were selected to represent the different cropping periods (i.e., rainfed and dry-season/irrigation) in the country. Lastly, the annual irradiation was derived by averaging the eight days selected and multiplying it by 365.

Water source availability was determined through use of the published groundwater maps by the British Geological Survey (i.e., groundwater level, aquifer productivity and groundwater storage all in a resolution of 5,000 m) and available river network for surface water (i.e., perennial rivers that have water in the dry season) provided by the Ministry of Water Resources of Ethiopia. The river network was used to determine a suitable distance of the solar pump from the river abstraction point. Given that small reservoirs are promoted and expanding rapidly in Ethiopia, the small reservoir feasibility map produced by FAO (FAO, 2012)[2] was also used to enable inclusion of surface water use from small water bodies (Table 1).

Several global land use maps are available that capture the change in land use over the past decades. However, these products overestimate the actual agricultural land given that scrubland is frequently misclassified as agriculture. Therefore, the consensus land use map (resolution 30 m) derived from Landsat in 2000 under the Woody biomass project (Ministry of Agriculture and Rural Development, 2005) was used in this study.

Finally, maps including road infrastructure from the Ethiopian Roads Authority (ERA) (Table 1) were used to obtain the distance to nearby roads. This information was considered to be relevant both for solar PV installation and maintenance purposes, as well as market access (i.e., accessing solar PV pumps and service providers, input markets, credit access, and output markets for selling agricultural products). The town map was available as point layer and included both town location and population size. During the multi-criteria assessment both road infrastructure and town maps were included separately to provide an estimation of market access. The assumption is that towns with a higher population would allow for agricultural products to travel over longer distances. Similarly, there would be a higher likelihood to access solar pumps, related accessories and maintenance (i.e., repair infrastructure) closer to large towns.

2.3. Technical specifications of solar PV pump

The lifting capacity of the pump and related solar energy requirement is an important input in assessing feasibility, as this also determines which water resources and geographical areas are suitable. While there is growing interest in the development of solar PV pump technology for both small- and large-scale farming, this study focused on smallholder options. Solar pumps that extract water from deep boreholes involve large capital investments generally beyond the affordability of smallholders and are not always readily available. Therefore, for this

[2] http://awm-solutions.iwmi.org/Data/Sites/3/Documents/PDF/Country_Docs/Ethiopia/ethiopia-awm-brief.pdf.

Table 1
Overview of the original spatial data used and associated derived maps.

Data	Spatial resolution (m)	Provider	Year
Original maps used			
Elevation	30	SRTM 30 m DEM 1 Arc second	2016
Rainfall	900	WorldClim (http://www.worldclim.org/)	2005
Groundwater level	5,000	British Geological Survey http://www.bgs.ac.uk/research/groundwater/international/africangroundwater/mapsDownload.html	2012
Aquifer productivity	5,000	British Geological Survey http://www.bgs.ac.uk/research/groundwater/international/africangroundwater/mapsDownload.html	2012
Water storage	5,000	British Geological Survey http://www.bgs.ac.uk/research/groundwater/international/africangroundwater/mapsDownload.html	2012
Land use & land cover	30	Woody Biomass Inventory and Strategic Planning Project (origin: LANDSAT) (Ministry of Agriculture and Rural Development, 2005)	2004
Irrigated land	250	International Water Management Institute (IWMI) (origin: Moderate Resolution Imaging Spectroradiometer [MODIS]) (available upon request) http://waterdata.iwmi.org/applications/irri_area/	2014
Depth to bedrock	250	International Soil Reference and Information Centre (ISRIC) (Hengl et al., 2015): http://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/bfb01655-db81-4571-b6eb-3caae86c037a.	2017
Town population	Point layer	Ethiopia - Woody biomass project (based on 1987 census). It was not used directly as input in the model, instead to derive proximity to town.	2004
Road	Vector	Ethiopian Roads Authority (ERA)	2010–2011
River	Vector	Origin: Ministry of Water Resources	2007–2008
National park	Vector	International Union for Conservation of Nature (IUCN) database	2010
Suitability for affordable lifting devices (small pumps)	Vector	FAO – Agwater solutions project (http://awm-solutions.iwmi.org/databases.aspx) (available upon request)	2012
Suitability for small reservoirs	Vector	FAO - Agwater solutions project (http://awm-solutions.iwmi.org/databases.aspx) (available upon request)	2012
Derived maps	**Spatial resolution (m)**	**Source**	
Slope	30	Derived in this study from SRTM 30 m DEM	2017
Aspect	30	Derived in this study from SRTM 30 m DEM	2017
Irradiation	30	Derived from elevation, slope and aspect	2017
Proximity to town	30	Derived from town population	2017

Table 2
Characteristics of both solar PV pump types used in the suitability mapping.

	Solar pump type I	Solar pump type II
Pump energy requirement (kWh)	0.3–0.4	0.8
Minimum irradiation threshold (kWh m^{-2})[a]	0.5	1
Suction head limitation (m)	7–8	20–30
Pump discharge (m^3/day) (7 h capacity/day)	6–13	25–35

[a] Minimum irradiation threshold used in the study.

feasibility analysis, small motorized pumps were chosen as a suitable option for smallholders, requiring a reasonable capital investment individually or in small farming groups. For smallholder farms of 1 ha, the maximum requirement for solar power is less than 1 kW (López-Luque, Reca, & Martínez, 2015). Hence, two solar pumps were selected requiring a minimum irradiation of 0.5 and 1 kWh m^{-2} with a suction head limitation of 7–8 and 30 m, respectively (Table 2). In cases where national governments, non-profit organizations, or private sector actors would plan for larger investments, bigger solar PV pumps could be included in the multi-criteria tool with simple modification (see section 2.4).

2.4. Multi-criteria model development for suitability analysis

Generally, a multi-criteria model has been applied to determine suitable sites for large-scale photovoltaic farms (Mahtta et al., 2014), smallholder irrigation or even ecotourism (Nino, Mamo, Mengesha, & Kibret, 2017; Worqlul et al., 2015, 2017). This study developed a multi-criteria model within an open source GIS environment (i.e., Quantum Geographic Information System [QGIS] with GRASS GIS) to assess the geo-spatial suitability of the two selected solar PV pumps for use with shallow groundwater or surface water. The technical requirements of the small solar pump technology (e.g. energy needed, suction head) (Table 2) were combined with pre-processed spatial maps (see section 2.2). The suitability analysis was carried out through three major steps (Fig. 2): (i) excluding areas that are not suitable for solar application (see section 2.4.1), (ii) reclassification to suitable classes for each factor (see section 2.4.2), and (iii) pairwise ranking and weighting of reclassified input maps (see section 2.4.2).

In total, four scenarios were established to assess the suitability of the two selected solar water-lifting devices. From the four scenarios, two accounted for only groundwater, one for only surface water (i.e., rivers and small water bodies) and two scenarios combined both surface water and groundwater resources: Scenario 1 included groundwater depths up to 25 m divided into two classes (0–7 m; 7.1–25 m); Scenario 2 considered very shallow groundwater (0–7 m) levels; Scenario 3 only accounted for the proximity to rivers or small reservoirs; and Scenario 4 combined both water resources (i.e., groundwater up to 25 m and surface water) (Table 3).

2.4.1. Constraints formulation

The various classes of each input map were evaluated against a defined set of land, water resource or climate-related constraints using the technical information of the selected solar pumps and prevailing limitations in the area of irrigation and agronomy (e.g. single cropping, double-cropping, short-cycle crops). Assuming the use of solar PV pumps both during the dry season as well as the rainfed season (i.e., supplementary irrigation), an average of 7.5 h of sunshine during the day and the minimum irradiation requirements of 0.5 kWh m^{-2} resulted in excluding irradiation below 1,300 kWh m^{-2} y^{-1}. The slope is an important factor in irrigated agriculture and slopes higher than 8% are not recommended given the erodibility of the soil, although some high-tech solutions (e.g. pressurized drip systems) would allow for

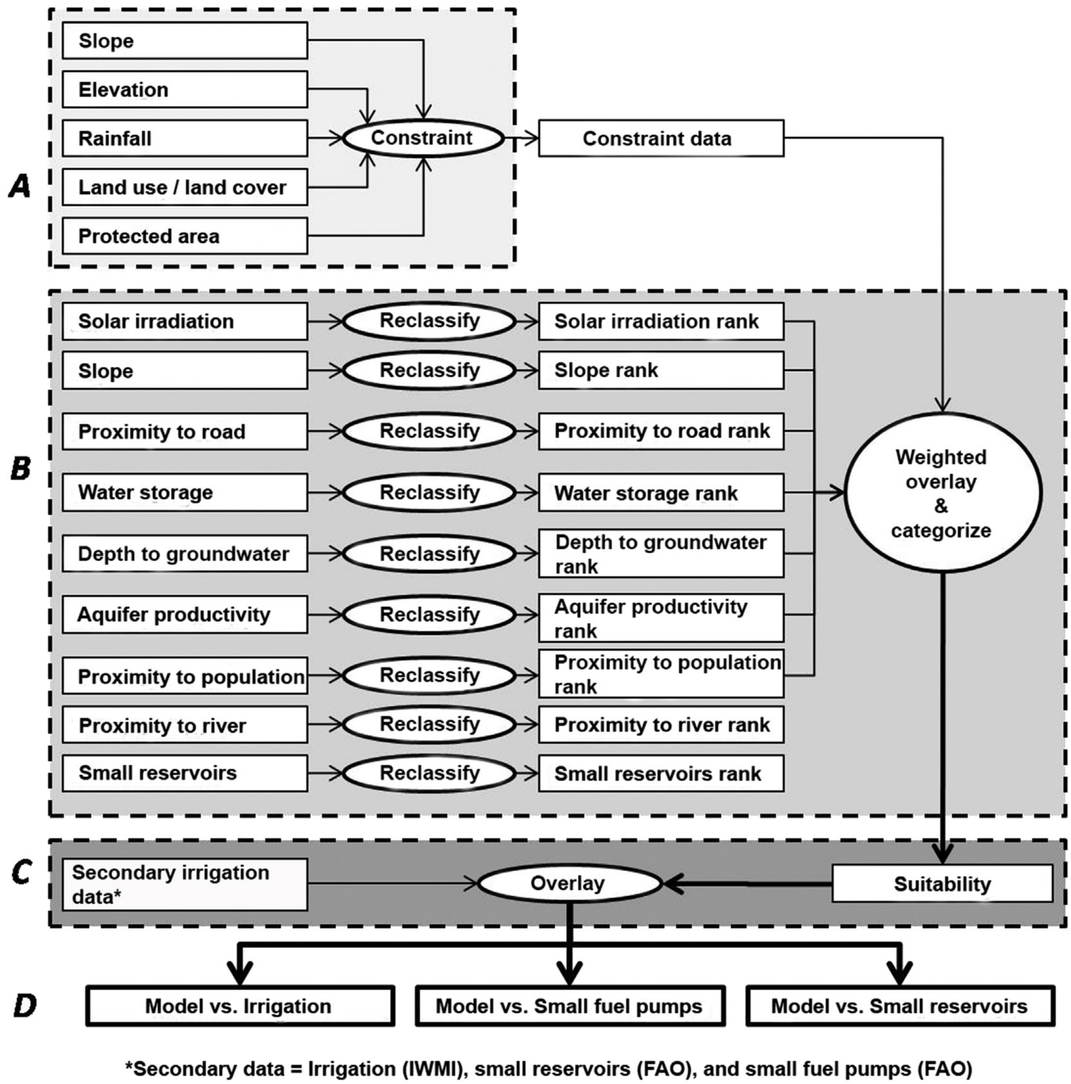

Fig. 2. Suitability framework developed for solar PV-based irrigation.

irrigated agriculture on slopes greater than 15%. In this study, the slope limit for sustainable gravitational irrigation was set at 8%. All constraints were consistent for all four scenarios with the exception of groundwater depth (supplementary data Fig. S1A through J). These criteria were used to exclude non-suitable areas in each map (Table 4).

The constraints were merged to derive two constraint data layers, one for groundwater up to 7 m and one for groundwater up to 25 m, revealing the potential suitable regions for the selected solar pumps (i.e., black areas in Fig. 3). The example for the constraint layer following the groundwater depth up to 25 m is shown in Fig. 3.

2.4.2. Identification of suitable areas: reclassification and suitability analysis

First, the classes in each map used in the suitability analysis were

Table 3
The factors considered in the multi-criteria model based on four different scenarios.

Data	Groundwater[a]		Surface water[a]	Groundwater & surface water[a]	
	Scenario 1	Scenario 2	Scenario 3	Scenario 4a	Scenario 4b
Solar irradiation (KWh m^{-2})	✓	✓	✓	✓	✓
Slope (%)	✓	✓	✓	✓	✓
Groundwater depth (0–7 m) I		✓		✓	
Groundwater depth (0–7, 7.1–25 m) II	✓				✓
Aquifer productivity (l/s)	✓	✓		✓	✓
Groundwater storage (mm)	✓	✓		✓	✓
Proximity to river (m)			✓	✓	✓
Proximity to small reservoirs (m)			✓	✓	✓
Proximity to roads (m)	✓	✓	✓	✓	✓
Proximity to town (m)	✓	✓	✓	✓	✓

[a] Scenario 1 included groundwater up to 25 m divided into two classes (0–7, 7.1–25); Scenario 2 considered very shallow groundwater (0–7 m) levels only; Scenario 3 covered only surface water: the proximity to rivers and the potential of small reservoirs (i.e., surface water); and Scenario 4 combined both water resources with scenario 4a including groundwater up to 7 m and scenario 4b including groundwater depth only up to 25 m.

Table 4
Criteria used to exclude unsuitable areas for solar pump irrigation.

Factor as constraint	Ranges of values as constraint within the factor
Protected areas	National parks, wildlife conservation areas (e.g. sanctuary), forest, wetland, lakes and dams
Land cover	Land cover other than agriculture, grass, shrub and bare land
Elevation[a]	Elevation below 500 m and higher than 3,200 masl
Rainfall[a]	Annual precipitation lower than 900 mm
Depth to bedrock	Depth to bedrock < 30 cm
Slope	Slope greater than 8%
Irradiation	Regions with a solar irradiation lower than 1,300 kWh m^{-2} y^{-1}
Groundwater depth	Groundwater depth of 7 m and 25 m as maximum limit
Groundwater storage	Low groundwater storage < 1,000 mm
Aquifer productivity	Less than 0.1 liters per second

[a] Elevation and rainfall were merged to create the constraint layer named agro-ecology. Areas below 500 m and with a precipitation lower than 900 mm are mainly the hot arid lowlands.

reclassified (Fig. 4) according to the following suitability classes: very highly suitable (score = 5), highly suitable (score = 4), moderately suitable (score = 3), less suitable (score = 2), least suitable (score = 1) and constraint (score = 0) (Table 5).

The reclassification of the solar irradiation was based on intervals of 500 kWh m^{-2} y^{-1} for the first two classes, 250 kWh m^{-2} y^{-1} for the following two classes and 200 kWh m^{-2} y^{-1} for the remaining class. The slope classification is based on the erodibility that surface irrigation could cause with 0–2% as very highly suitable (Worqlul et al., 2017), 2 to 4% as highly suitable and 4–8% as moderately suitable. Only the first two classes from the groundwater map, produced by MacDonald et al. (2012), were used (0-7 m and 7.1 – 25 m) to produce the reclassified input map. Given the differences in lifting characteristics between the two pumps, two maps were produced: one groundwater map only had one class 0–7 m (highly suitable for both solar pump types) and the other had two classes: 0–7 m (very highly suitable for both solar pump types) and 7.1–25 m (highly suitable only for solar pump type II). According to MacDonald et al. (2012) an intermediate borehole yield of 0.5–5 l s^{-1} is sufficient for smallholder irrigation. Hence, everything above 0.5 l s^{-1} was considered as very highly suitable. Given the average discharge of solar pump type I of around 0.1 to 0.25 l s^{-1}, the class 0.5–0.1 l s^{-1} was still considered as highly suitable whereas everything lower was removed in the constraint analysis. The reclassification of the groundwater storage followed the classes identified by MacDonald et al. (2012) from highly suitable to suitable. The reclassification of the calculated distance to the river and small reservoirs was based on the feasibility of conveying the water after lifting. The reclassification of the proximity to town included both the distance to the nearest town and the population density, with the larger distance and higher population density being most suitable given the higher probability of access to technology as well as credit.

Second, a pairwise comparison matrix was applied to the reclassified maps according to the well-established method by Saaty (1977). The weighting factors were initially determined based on expert knowledge and then fine-tuned through various model iterations, while evaluating the sensitivity of the model output for the various scenarios (i.e., the suitability maps) (Table 6). Consistency between the weights given to the various factors was checked using the consistency rate, which is the ratio between the consistency index and the random index.

The pairwise weighting factors applied for each factor were the same in Scenarios 1 and 2 given that the difference between both scenarios is only the constraint for the groundwater table depth. For Scenario 3, the proximity to river and small reservoirs was given the same weighting factor as the groundwater depth in Scenarios 1 and 2. However, given the higher number of factors considered in Scenario 3, compared to Scenarios 1 and 2, this resulted in different effective weighting. For the combined analysis of both groundwater and surface water in Scenarios 4a and 4b, the groundwater-related factors (i.e., groundwater depth, aquifer productivity and groundwater storage) overshadowed the other water-related factors (i.e., proximity to river and small reservoirs). Therefore, each of the groundwater-related factors were first evaluated against the others within their group. Then, the group was compared against all other factors to obtain the final weights (Table 6). This was done for groundwater depths of up to 7 m and 25 m separately resulting in Scenarios 4a and 4b, respectively.

Finally, the suitability map was created for each scenario by aggregating the different factors considering the weight of each factor. A filter was applied on the suitability maps produced to eliminate isolated cells using a threshold of 100 ha. The assumption was that, for small isolated areas, the market would not be available to purchase or

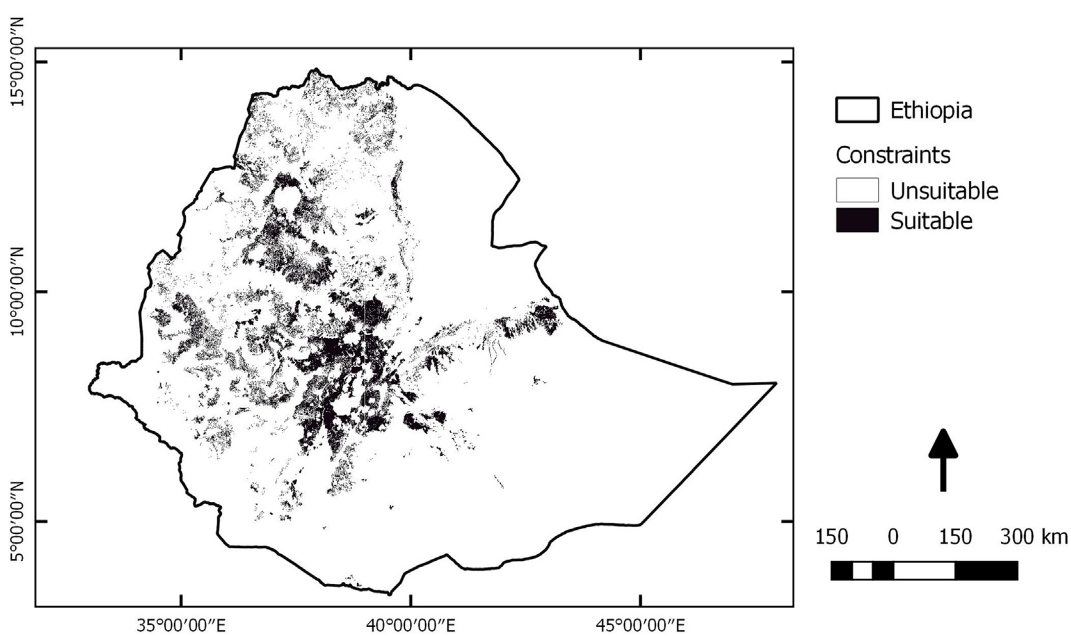

Fig. 3. Merged map based on individual constraints indicated in Table 4. For individual constraint maps, refer to supplementary Fig. S1. The potential areas after constraint analysis in the merged map are represented in black.

maintain solar PV pumps. Furthermore, the values of the aggregated layer for each scenario were reclassified into very highly suitable (class 1: 4.5–5), highly suitable (class 2: 3.5–4.5), moderately suitable (class 3: 3.5–3.0), less suitable (class 4: 3.0–2.0) and least suitable (class 5: 2.0–1.0). Values below 1.0 were considered unsuitable. For each scenario, the suitable area for solar PV pump-based irrigation was aggregated at regional administration level.

2.5. Comparison of the suitability maps with available data

2.5.1. Uncertainty of groundwater depth information

Well-depth information from 127 geo-referenced wells were measured under the Feed the Future Innovation Lab for Small-Scale Irrigation (ILSSI) project by the International Water Management Institute (IWMI) and provided for the comparison analysis (Nakawuka et al., 2016). These data were compared with the suitable areas identified from Scenarios 1, 2 and 4. Information was available for a total of 83 wells located in Amhara Region, 22 in Oromia Region and 22 in SNNPR. The well depth was compared with the groundwater depth classification of 0–7, 7.1–25 m and 0–25 m.

2.5.2. Suitability of solar PV pumps in irrigated and rainfed agriculture

The maps produced by the four scenarios were overlaid with the irrigated area map of Africa from 2014 published by IWMI (http://waterdata.iwmi.org/applications/irri_area). The use of the identified solar PV pump potential with existing irrigated land and rainfed

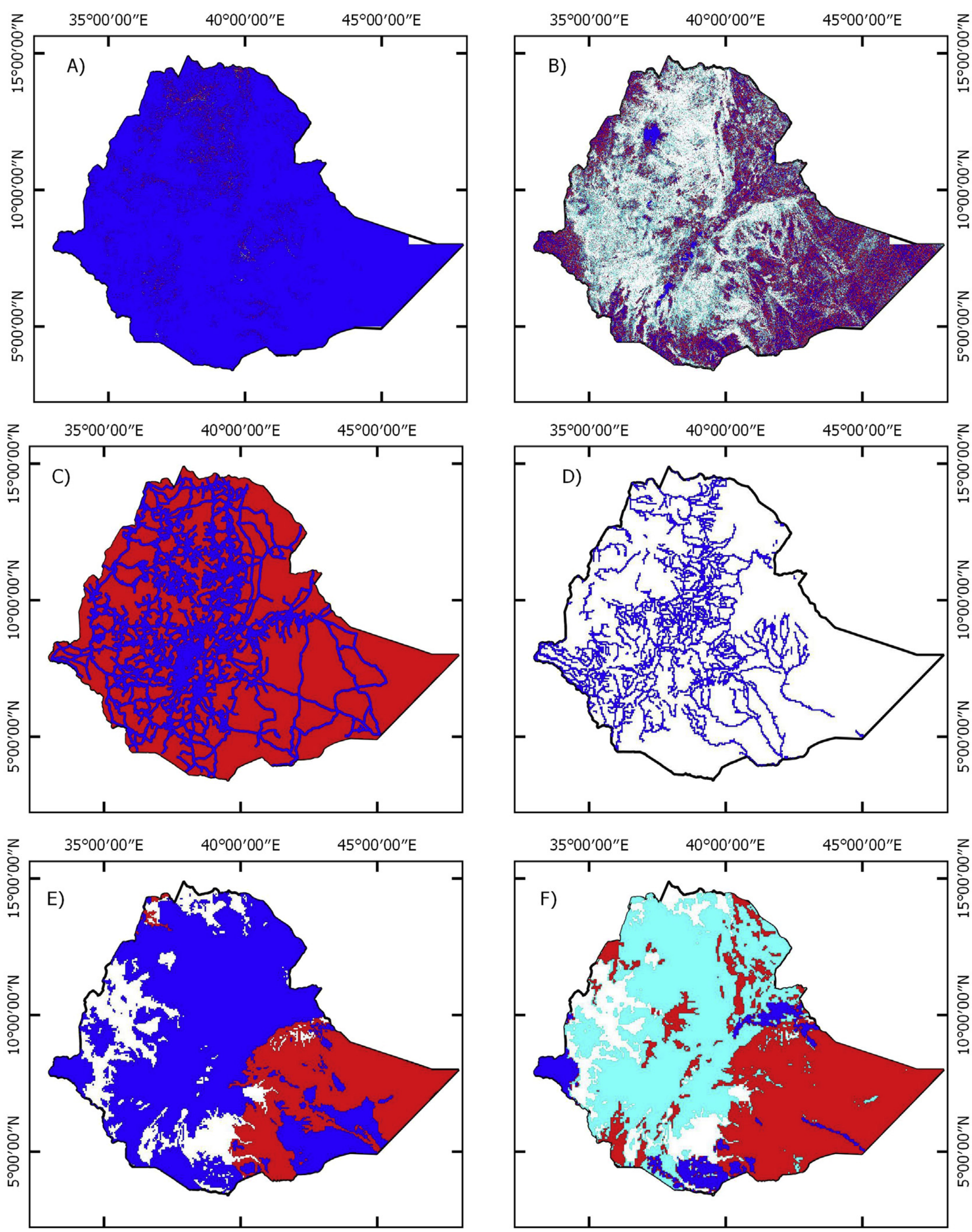

Fig. 4. Reclassification maps for: A) solar irradiation, B) slope, C) proximity to road, D) depth to groundwater, E) aquifer productivity, F) groundwater storage, G) proximity to river, H) proximity to small reservoir, and I) proximity to town (population density dependent).

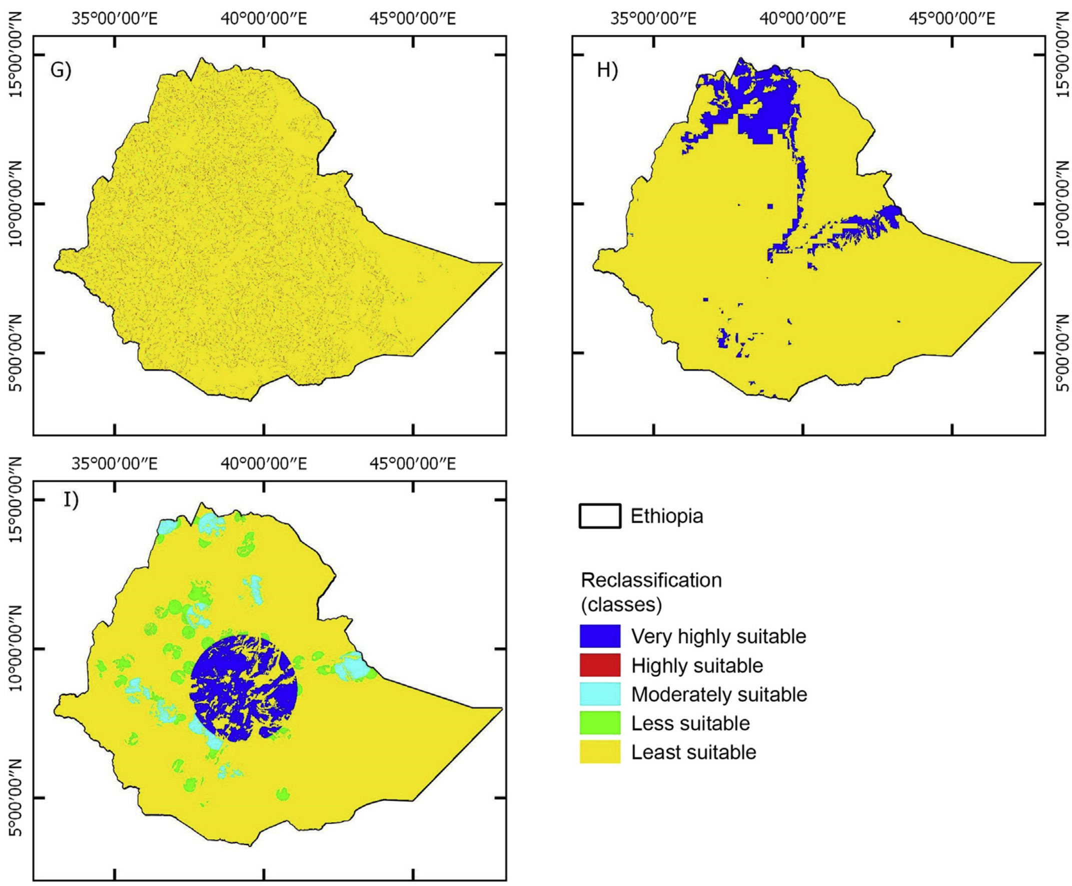

Fig. 4. (*continued*)

Table 5
Reclassification criteria used for the various maps included in the multi-criteria analysis.

Factor	Very highly suitable = 5	Highly suitable = 4	Moderately suitable = 3	Less suitable = 2	Least suitable = 1	Constraint = NULL
Solar irradiation (kWh m^{-2} y^{-1})	3,000–2,500	2,499–2,000	1,999–1,750	1,749–1,500	1,499–1,300	< 1,300
Slope (%)	0–2	2–4	4–8	NA	NA	> 8
Groundwater depth (0–7 m) I[a]	0–7	NA	NA	NA	NA	> 7
Groundwater depth (0–25 m) II[a]	0–7	7.1–25	NA	NA	NA	> 25
Aquifer productivity (l/s)	> 0.5	0.5–0.1	–	–	–	< 0.1
Groundwater storage (mm)	25,000–50,000	10,000–25,000	1,000–10,000	–	–	< 1,000
Proximity to river (m)	< 50	51–100	101–200	201–300	> 300	–
Proximity to small reservoirs (m)	< 50	51–100	101–200	201–300	> 300	–
Proximity to town (m)	200 km	100 km	50 km	25 km		–
and population	> 100,000	45,000–100,000	15,000–45,000	2,500–1,500		

[a] NA = not applicable due to the limitation of the selected solar pump types.

agriculture would yield valuable information on where solar PV irrigation could replace existing irrigation technologies or where it could transform rainfed agriculture. The irrigated map for Africa was derived using MODIS imagery from 2010 with a resolution of 250 m encompassing seven classes: irrigated land-single crop, irrigated land-double crop, irrigated land-triple crop, residual soil moisture-single crop (not irrigated), residual soil moisture-double crop (not irrigated), rainfed-single crop and rainfed-double crop. For the analysis, the seven classes were grouped into two categories: irrigated (combination of all three irrigated classes) and rainfed (combination of the remaining four classes). According to the map, a total of 22,044 10^3 ha is agricultural land, of which 1,049 10^3 ha is irrigated and 20,995 10^3 ha is rainfed.

2.5.3. Suitability of solar PV pumps as an alternative to small reservoirs or hydrocarbon fuel pumps

In the final step, the spatial distribution of the suitable areas for the four scenarios was compared to the feasibility maps for small reservoirs and small hydrocarbon fuel pumps developed for Ethiopia by FAO (FAO, 2012) (Fig. 2). The comparison of the small reservoir map with the suitability output of Scenarios 1, 2 and 4 provided information on whether the solar pump using groundwater resources overlapped with the potential establishment of small reservoirs. The comparison of the small motorized hydrocarbon fuel pump suitability map with the output from various solar pump suitability scenarios can provide information on the portion of hydrocarbon fuel pump suitability that could be transformed into solar energy-based water lifting for irrigation purposes. Important to note is that the comparison did not include an economic evaluation of investment, maintenance or operation cost for small reservoirs or hydrocarbon fuel pumps, as the sole aim was to identify areas where alternative solutions could potentially occur. This information is relevant to governments and other agencies involved in providing irrigation infrastructure support, as it would indicate the

Table 6
Weighting factors derived for the four different scenarios following a pairwise comparison.

Data	Groundwater[a]		Surface water[a]	Groundwater & surface water[a]	
	Scenario 1	Scenario 2	Scenario 3	Scenario 4a	Scenario 4b
Solar irradiation (KWh m^{-2})	0.26	0.26	0.27	0.17	0.17
Slope (%)	0.09	0.09	0.13	0.07	0.07
Distance to roads (m)	0.04	0.04	0.05	0.03	0.03
Groundwater depth (0–7 m) I	–	0.26	–	0.17	–
Groundwater depth (0–7, 7.1–25 m) II	0.26	–	–	–	0.17
Aquifer productivity (l/s)	0.15	0.15	–	0.10	0.10
Groundwater storage	0.15	0.15	–	0.10	0.10
Proximity to river	–	–	0.25	0.17	0.17
Proximity to small reservoirs	–	–	0.25	0.17	0.17
Proximity to town	0.04	0.04	0.05	0.03	0.03
Consistency rate[b]	*−0.76*	*−0.76*	*−0.81*	*−0.68*	*−0.68*

[a] Scenario 1 included groundwater up to 25 m divided into two classes (0–7, 7.1–25); Scenario 2 considered very shallow groundwater (0–7 m) levels only; Scenario 3 covered only surface water: the proximity to river and the potential of small reservoirs (i.e., surface water); and Scenario 4 combined both water resources with scenario 4a including groundwater up to 7 m and scenario 4b including groundwater depth only up to 25 m.
[b] Consistency rate = consistency index/random index following Saaty (1977).

areas that require an in-depth economic feasibility study (e.g. solar PV business models) before decisions are made on the type of infrastructure (Otoo et al., (2018)).

3. Results

3.1. Suitability under different water availability scenarios

Across Scenarios 1, 2 and 3, the weighting factor assigned for a particular input map showed a relatively equal importance (Table 6). For example, the weighting factor for solar irradiation was 0.26 in Scenarios 1 and 2 and 0.27 in Scenario 3 as it was given equal importance in the groundwater and surface water scenarios. Additional groundwater characteristics (i.e., aquifer productivity and groundwater storage) in Scenarios 1 and 2 were found less important than groundwater depth and solar irradiation but more important than slope and distance to roads or proximity to towns. For Scenario 4, the absolute weighting of the maps was slightly different due to the number of factors included to accommodate both surface water and groundwater resources together. However, the relative order of the weighting factors was similar to those of Scenarios 1, 2 and 3 with solar irradiation, groundwater depth, and proximity to river and small reservoirs followed by groundwater storage and aquifer productivity, slope, proximity to town and distance to roads.

Total estimated suitable area when combining both surface water and groundwater up to 25 m is around 6,810 10^3 ha (Scenario 4b, Fig. 5 E), which drops to 6,304 10^3 ha (Scenario 1, Fig. 5 A) when only groundwater is considered (Table 7). The use of very shallow solar pumps with a suction head of 7 m would be suitable for 2,177 10^3 ha (Scenario 2, Fig. 5 B). When including surface water, the coverage would be approximately 2,751 10^3 ha (Scenario 4a, Fig. 5 D). The lowest suitable area (1,136 10^3 ha) was found when only surface water was considered (Scenario 3, Fig. 5 C).

By administrative region, the largest suitable area for solar PV pump irrigation using groundwater resources was found in Oromia Region followed by Amhara Region and SNNPR (Scenarios 1, 2, 4a and 4b, Fig. 5). The smallest suitable area was found in Harar Region followed by Addis Ababa as the major land use type in both regions reflects the urban build up and hence those areas were discarded during the constraint analysis (see supplementary material S1 F).

When using surface water, the highest potential for solar PV development was found in Oromia Region followed by Tigray, Amhara and Somali regions (Scenario 3, Table 7). The higher potential in Tigray compared to Amhara is related to the potential of small reservoirs. Similarly, the increase in the potential area for Somali when comparing Scenario 3 with Scenarios 1 and 2 can be explained (Fig. 4H). On the other hand, the lowest suitable area is found in the peri-urban area of Addis Ababa followed by Gambella, Benshangul Gumuz and Harar (Table 7). Results obtained for Addis Ababa were similar to those found in the groundwater-related scenarios. Additionally, the land use in Gambella and Benshangul Gumuz mainly consists of forest (see supplementary material S1 F) and protected areas (see supplementary material S1 J). Therefore, those areas were discarded during the constraint analysis. Furthermore, the agro-ecology in Gambella covers both hot sub-humid and warm semi-arid lowlands (Fig. 1) characterized by high temperatures given its low elevation (500 masl) (Table 4). These areas were removed during the constraint analysis. For Benshangul Gumuz, the absence of small reservoir potential (see supplementary material S1 H) and the low presence of perennial rivers limits the area for surface water-based abstraction. On the other hand, given the high suitability for small reservoirs in Harar, located in the Eastern Ethiopian highlands, the solar PV suitability area calculated following Scenario 3 is higher compared to those obtained in Harar in Scenarios 1 and 2.

3.2. Comparison of suitability maps with existing data

3.2.1. Uncertainty of groundwater depth information

The available geo-referenced wells from the ILSSI project and their respective depth were compared with the suitable solar PV-based irrigation areas identified. From 127 geo-referenced shallow wells noted above, 77% were situated in suitable and 23% in unsuitable areas (Table 8).

Overall, the agreement of the 0–7 m well depth class is lower compared to the 7.1–25 m class. Investigating the 98 wells located in the suitable area showed a 73% agreement with the 0–7 m class whereas 81% correspondence was found with the 7.1–25 m class. The variability in correspondence also varied across the regions (Table 8). For the 0–7 m groundwater class, the highest agreement was found in Jawe and Upper Gana villages of SNNPR (Fig. 6D) while the lowest agreement was found in Bochessa village of the Oromia region (Fig. 6E). In Robit and Dangishta, 78% and 68% corresponded with the 0–7 m class, respectively (Fig. 6B and C). In the 7.1–25 m class, the few wells in Jawe, Upper Gana and Bochessa all corresponded with the well depth class. In Amhara region, 50% of the wells in Dangishta and 80% of the wells in Robit corresponded with the lower well depth class (Table 8).

3.2.2. Suitability of solar PV pumps in irrigated and rainfed agriculture

Depending on the scenario, the land identified as suitable for solar PV-based irrigation overlapped, on average, with 9% of the total area

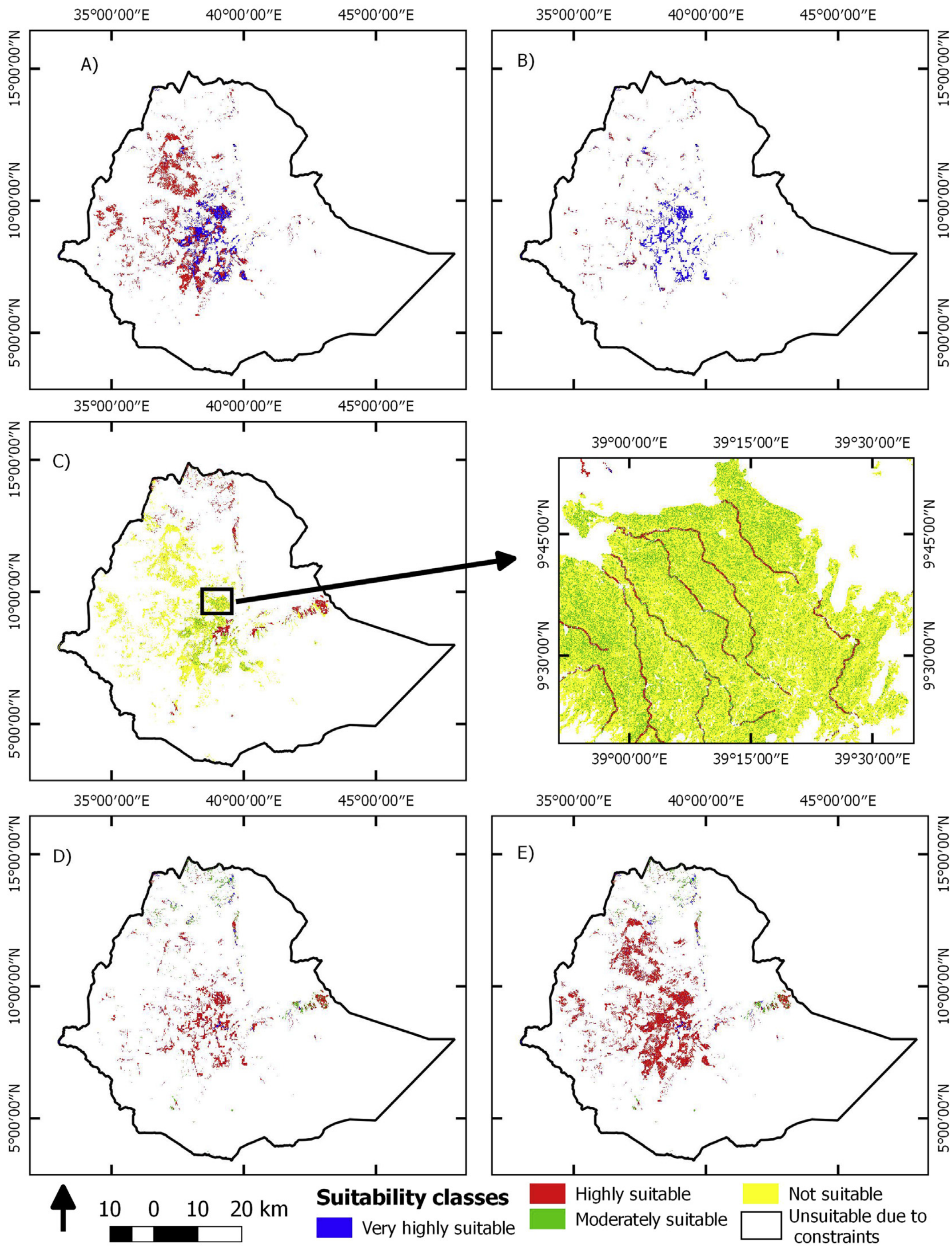

Fig. 5. Suitability maps: A) Scenario 1; B) Scenario 2; C) Scenario 3; D) Scenario 4a; and E) Scenario 4b with groundwater depth up to 25 m. Only the first three suitability classes are shown (i.e., very highly suitable, highly suitable and moderately suitable).

and ranged between 45 10^3 ha and 167 10^3 ha (Table 9, Fig. 7). In those areas, solar PV pumps could be considered by smallholders already practicing irrigation. The largest overlap (i.e., 167 10^3 ha, 16%) was found for Scenario 4b where both groundwater up to 25 m and surface water resources were combined. On the other hand, the lowest (i.e., 45 10^3 ha) overlap was found for Scenario 3. For Scenario 4b, the suitability of solar PV pumps corresponding with irrigated land was highest in Oromia and Amhara regions. Comparing the areas suitable for solar irrigation with rainfed agricultural land showed a potential between 18% (1,091 10^3 ha) and 32% (6,642 10^3 ha) of solar PV-based pumps with the highest potential achieved in Scenarios 1 and 4b (Table 9, Fig. 7). In those areas, results show that groundwater resources are available and could be potentially lifted through solar PV-based pumps for either supplementary irrigation in the rainy season or to support smallholder agriculture during the dry season.

According to the suitability analysis, between 882 10^3 ha and 1,004 10^3 ha of irrigated land would not be suitable for small solar PV pumps due primarily to access to water resources, elevation or slope not fulfilling the criteria given their respective weights in the scenarios (Table 5).

3.2.3. Suitability of solar PV pumps as an alternative to small reservoirs

Scenario 3 showed that 1,020 10^3 ha of the area suitable for small reservoir implementation would be suitable for water extraction using small solar PV pumps (Table 9, Fig. 8).

Additionally, another 116 10^3 ha along rivers were found to be suitable in the absence of small reservoirs. Scenarios 1 and 2, on the other

Table 7
Regional and total suitable area (10^3 ha) for solar-based pump irrigation following four scenarios. Only the highly suitable and suitable areas were considered.

Region	Total suitable area in 10^3 ha				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4a	Scenario 4b
Addis Ababa	2	0.6	0.2	0.7	2
Afar	8	8	2	8	8
Amhara	1,776	371	202	446	1,834
Beneshangul Gumuz	21	5	0.5	5	21
Gambella	16	8	0.4	9	16
Harar	0.4	0.4	0.8	0.7	0.7
Oromia	3,337	1,443	463	1,716	3,569
SNNPR[a]	1,077	282	41	298	1,087
Somali	10	8	154	125	125
Tigray	57	51	272	143	147
Total	**6,304**	**2,177**	**1,136**	**2,751**	**6,810**

[a] Southern Nations, Nationalities, and People's Region.

hand, showed that between 155 10^3 ha (Scenario 2) and 204 10^3 ha (Scenario 1) could be irrigated either using small reservoirs or shallow groundwater (Fig. 8). In those areas, smallholder farmers would have the option to choose or sustain irrigation using groundwater, if the surface water available from small reservoirs or rivers would be insufficient. In Scenarios 4 a and b, the areal overlap between the suitability maps of solar PV pumps and the small reservoirs decreased from 1,020 10^3 ha (i.e., Scenario 3) to 669 10^3 ha and 689 10^3 ha, respectively. This decrease in area compared to Scenario 3 could be attributed to the merging of both groundwater and surface water factors, and giving less weight to the small reservoir and river proximity factor (Table 6).

Around 8,410 10^3 to 9,274 10^3 ha of land was found to be suitable for small reservoir implementation but unsuitable for solar-based PV irrigation, which corresponded with a difference of 56% to 88% between both maps. Hence, farmers would either be dependent on gravitational release from the small reservoirs or use other solar PV pump types or lifting technologies. These areas were mainly located in Tigray, Amhara and Oromia regions which can be explained mainly by excluding deeper groundwater tables, slopes higher than 8% and non-agricultural land cover (Fig. 4).

3.2.4. Suitability of solar PV pumps as an alternative to hydrocarbon fuel pumps

The comparison of the suitability maps for solar PV pumps and small hydrocarbon fuel pumps shows the potential of the two solar pump types to replace small motorized pumps in the context of climate-smart agriculture. Using groundwater resources, solar PV pumps could provide an alternative water-lifting option for smallholder farmers to small motorized fuel pumps in 1,267 10^3 ha when well depths are up to 7 m and in 3,934 10^3 ha when well depths are up to 25 m (Table 9 and Fig. 9). Including surface water would increase the potential to 1,371 10^3 ha and 4,010 10^3 ha for scenarios 4a and 4b, respectively. Only considering potential small reservoirs or perennial rivers would result in an area of 247 10^3 ha.

The area that would be suitable for solar pumps but was not identified as a potential area for small hydrocarbon fuel pumps covered between 888 10^3 ha and 2,799 10^3 ha depending on the water resources and solar pump type. This area corresponded with a difference between 5% and 13% between both maps (Fig. 9). The discrepancy might be related to the differences in water resource maps used in this study compared to those used to derive the suitable hydrocarbon fuel pump map. On the other hand, between 68% (14,181 10^3 ha) and 89% (17,944 10^3 ha) was found to be suitable for small hydrocarbon fuel pumps but not for the selected solar PV pump types tested in this study (Fig. 9).

4. Discussion

4.1. Uncertainty of data used in multi-criteria analysis for solar PV pumps

The weighting and the accuracy of water-related input as well as solar irradiation played an important role in the assessment. According to Huld et al. (2012), differences between solar irradiation estimates using different solar data is apparent in mountainous areas such as East Africa, which could be attributed to the method used for downscaling. This should be taken into account when selecting the appropriate estimates from sources such as the PVGIS. Furthermore, with smallholder farmers having a size of 1 ha or less, solar irradiation estimates require a fine resolution, especially in the mid-highlands and the highlands in Ethiopia. Hence, a high resolution DEM was used to account for slope and aspect ratios influencing solar irradiation. Although only eight days were used to calculate annual irradiation values, the uncertainty will be small compared to those obtained in temperate zones using the eight-day method, given that in sub-tropical regions such as Ethiopia the daylight fluctuation is relatively low throughout the year. With an increasing interest in solar technologies, solar irradiation products are improving and becoming more readily available both as open source as well as commercial products with a finer resolution (Huld, 2017).

Aside from solar irradiation, the main input for Scenarios 1, 2 and 4 was the spatial groundwater data established for Africa by the British Geological Survey (MacDonald et al., 2012). The study uses 283 aquifer summaries from 152 publications throughout the continent. Comparing the groundwater level map with data available from the ILSSI project showed an acceptable overlap for shallow groundwater within the 0–25 m class but a relatively high uncertainty for the 0–7 m class. The high uncertainty of the very shallow groundwater zone together with its coarse resolution of 5 km strongly influenced the suitability of solar pump type I selected in this study. Improving the resolution and accuracy of shallow groundwater availability would in turn increase veracity of the current estimates for potential solar PV-based pumping.

Furthermore, MacDonald et al. (2012) reported that in many African countries, well-established boreholes would be able to supply between 0.1 and 0.3 $l\,s^{-1}$, which is suitable for hand pumps. For Ethiopia, aquifer productivity mainly ranges between 0.1 and 0.5 $l\,s^{-1}$ (Fig. 4). Whereas the average discharge of the solar PV pump type I (Table 2) would, depending on the water level, largely fall within this range, the second type

Table 8
Number of observations (N) and level of agreement (%) of the shallow well information with the suitability classes according to the groundwater table depth of 0–7 m, 7.1–25 m and 0–25 m for Scenario 1, which combines two groundwater depth classes and excludes surface water.

Region	Village	Well depth 0–7 m			Well depth 7.1–25 m			Well depth 0–25 m		
		N	Suitable (%)[a]	Unsuitable (%)	N	Suitable (%)[a]	Unsuitable (%)	N	Suitable (%)[b]	Unsuitable (%)
Amhara	Robit	9	78	22	46	80	20	55	80	20
Amhara	Dangishta	22	68	32	6	50	50	28	64	36
SNNPR	Jawe	4	100	0	6	100	0	10	100	0
SNNPR	Upper Gana	10	100	0	2	100	0	12	100	0
Oromia	Bochessa	18	56	44	4	100	0	22	64	36
Total			*73*	*27*		*81*	*19*		*77*	*23*

[a] For the 0–7 m and the 7.1–25 m well classes, the agreement percentage refers to those wells with well depth corresponding to the respective classes.
[b] The specific depth class of the well is not taken into account. The agreement only considered whether the well depth is within the 0–25 m category.

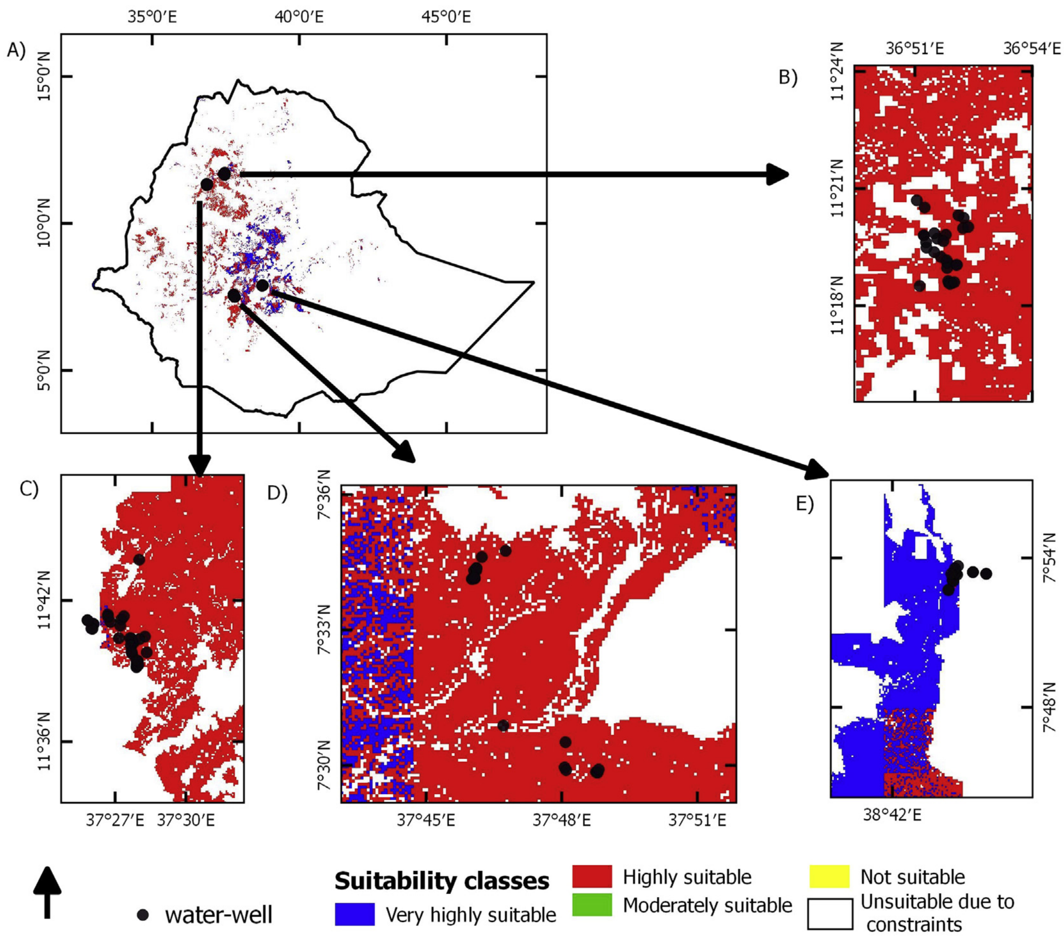

Fig. 6. Location of water well points (black dots) according to Scenario 1 for a) Ethiopia, and zoomed in for b) Robit village (Amhara region), c) Dangishta village (Amhara Region), d) Jawe and Upper Gana villages (SNNPR), and e) Bochessa village (Oromia region). Only the first three suitability classes are shown (i.e., very highly suitable, highly suitable and moderately suitable).

would have a much larger abstraction rate. In the latter case, the abstraction might be higher than the sustainable aquifer productivity. This could lead to over-abstraction when solar PV pumps such as type II are being promoted. Although the aquifer productivity was included in the multi-criteria analysis, the smaller weighting factor compared to the groundwater depth might result in an over-estimation of the feasibility of solar pump type II in some locations.

The availability of surface water in this study was approximated using the identified suitability of small reservoirs by FAO (2012) and combined with the distance to perennial rivers. The methodology used in defining suitable areas for small reservoirs included a runoff estimation map with its own uncertainty. Estimating national runoff is often challenging due to lack of available data for calibration and validation of models. With the ongoing advances in modeling as well as high resolution rainfall and soil information products, these estimates could improve in the future. However, comparing the discrepancy between the suitable small reservoir map and the areas suitable for solar PV in Scenario 3 shows that the main factors for solar unsuitability were most likely slope and land cover. Hence, combining solar PV pumping with water-efficient technologies such as drip could overcome the 8% slope restriction set in the model. This most likely would lead to a higher areal estimation for Scenario 3.

The land use map, dated from 2000, shows discrepancies with the agricultural map produced by IWMI (http://waterdata.iwmi.org/applications/irri_area). Notwithstanding the different methodologies used when deriving respective maps, the agricultural land estimates using MODIS 2010 show a clear increase in agricultural land use. There are ongoing advances in land use classification and associated products are being developed using high resolution imagery (Kibret, Marohn, & Cadisch, 2016). Applying these products in the solar suitability model

Table 9
Overlapping area (ha) between the suitability obtained for solar PV pumps following the four scenarios and the available maps on irrigated land (http://waterdata.iwmi.org/applications/irri_area), suitability of small reservoirs (FAO, 2012) and suitability of small motorized fuel pumps (FAO, 2012). Values are obtained from Figs. 7–9, respectively.

	Irrigated land (10^3 ha)			Small dams (10^3 ha)			Small motorized fuel pumps (10^3 ha)		
	Solar & irrigated Land[a]	Solar & rainfed land[a]	No solar & irrigated land	Solar & small reservoirs	Solar & no small reservoirs	No solar & small reservoirs	Solar & small fuel pumps	Solar & no small fuel pumps	No solar & small fuel pumps
Scenario 1	144	6,159	905	204	6,099	9,226	3,934	2,369	14,259
Scenario 2	50	2,126	999	155	2,021	9,274	1,267	909	16,925
Scenario 3	45	1,091	1,004	1,020	116	8,410	247	888	17,944
Scenario 4 a	74	2,677	975	669	2,082	8,761	1,371	1,380	16,821
Scenario 4 b	167	6,642	882	689	6,120	8,740	4,010	2,799	14,181

[a] The total irrigated and rainfed land according to IWMI (http://waterdata.iwmi.org/applications/irri_area) are 1,049 10^3 ha and 20,995 10^3 ha, respectively.

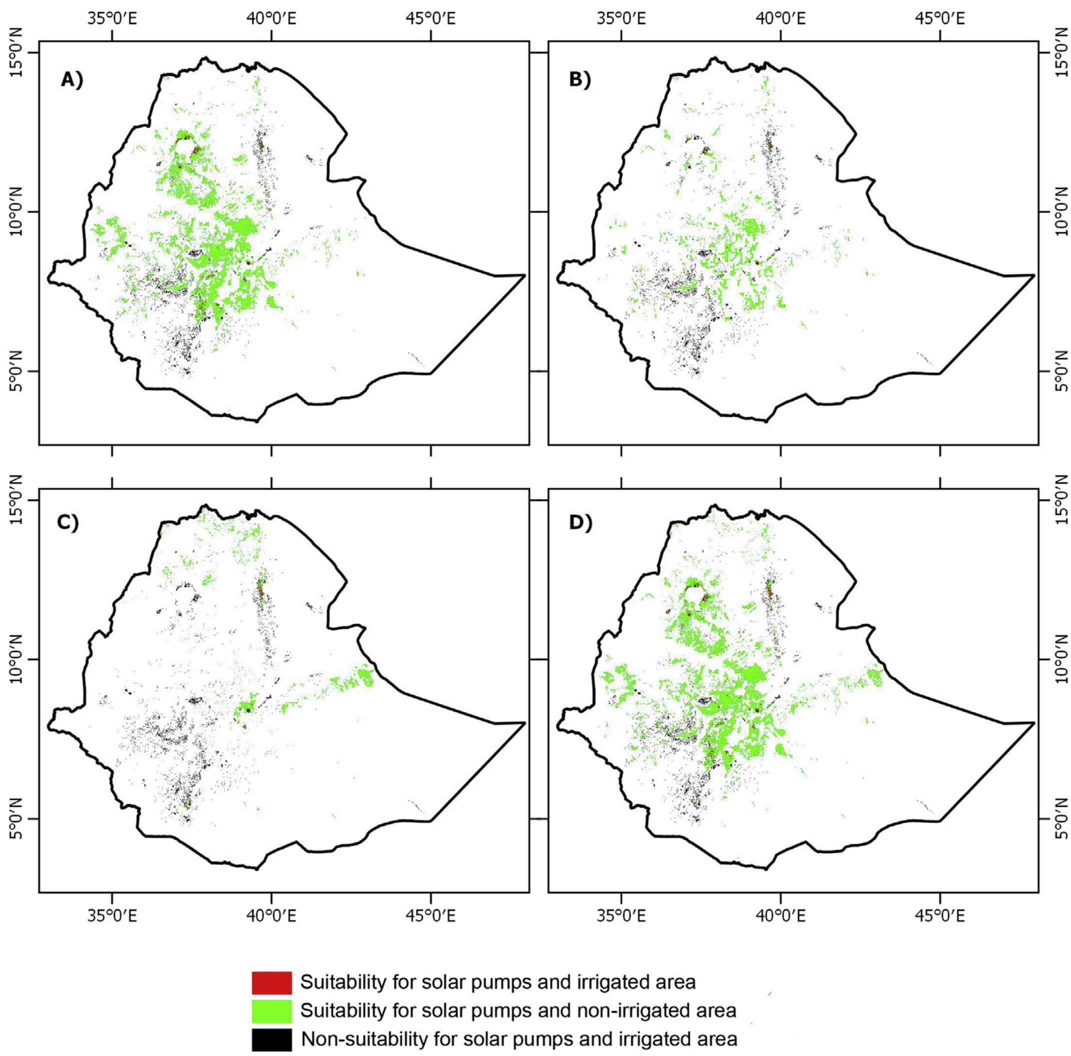

Fig. 7. Comparison of the solar suitability scenarios against the irrigated area mapped in 2010.
(source: IWMI: http://waterdata.iwmi.org/applications/irri_area) A) Scenario 1, B) Scenario 2, C) Scenario 3, D) Scenario 4a, and E) Scenario 4b.

could increase estimates for solar-based irrigation on current irrigated and rainfed lands, which together might well exceed 167 10^3 ha and 6,642 10^3 ha (Scenario 4b), respectively. Furthermore, combining the model inputs with recently developed suitability maps for irrigated land (e.g. Worqlul et al., 2017) could provide further insights into the importance of both land use and water resource uncertainty.

Aside from uncertainty in the input maps, the second aspect affecting uncertainty is the reclassification and weighting of the different factors. To reduce the model uncertainty, a pairwise comparison was applied to improve model consistency according to Saaty (1977). In this study, the main purpose was to evaluate where irradiation criteria of the solar pump types were met and where groundwater and surface water would be sufficiently available. Hence, the approximation to markets (i.e., town population and distance to roads) received slightly lower values than the slope factor and considerably lower weighting than the irradiation, groundwater depth and proximity to river. Thus, while the weighting results (Table 6) show an acceptable consistency between all four scenarios, the suitable areas identified are highly dependent on the prioritization of biophysical factors. While the multi-criteria model approach is frequently used, the development of the model highly depends on the main purpose of the suitability analysis (Akyol et al., 2016; Palmas et al., 2012; Venkatesan et al., 2010; Worqlul et al., 2015; Yalcin & Kilic Gul, 2017). For example, if the main aim was to assess market potential for solar PV pumps including maintenance services and spare parts, higher weighting would be given to the distance to roads and proximity to towns, resulting in potentially different suitability maps. Therefore, stakeholders using the suitability maps derived in this study should acknowledge the prioritization of biophysical over market-related factors. However, the framework does provide a good basis for further analysis which should be strongly embedded within the socio-economic context relevant in those specific locations.

4.2. Potential of solar PV irrigation as a climate-smart technology in SSA

The lack of sufficient electricity infrastructure across most rural areas in SSA is one of the main hindrances to the transition from purely rainfed to intensified irrigated agriculture (Amjath-Babu et al., 2016). Motorized hydrocarbon-based fuel pumps are often the only option for farmers. According to Scenario 4b, small solar PV pumps could provide an alternative to small hydrocarbon fuel pumps in 4,010 10^3 ha. This would reduce fossil fuel consumption and hence positively affect greenhouse gas emissions. Xie et al. (2014) estimated that through efficient use of available surface water and groundwater resources in SSA, the use of hydrocarbon fuel pumps could increase small-scale irrigable land by 30 Mha benefiting 180 million people and resulting in an annual net revenue of USD 22 billion. Applying the model developed to SSA could help to identify areas where solar-based PV pumping could provide a suitable alternative, contributing to a reduction in fuel consumption and associated greenhouse gas emissions. However, further analysis of the identified areas is necessary to enable technology scaling. Otoo et al.

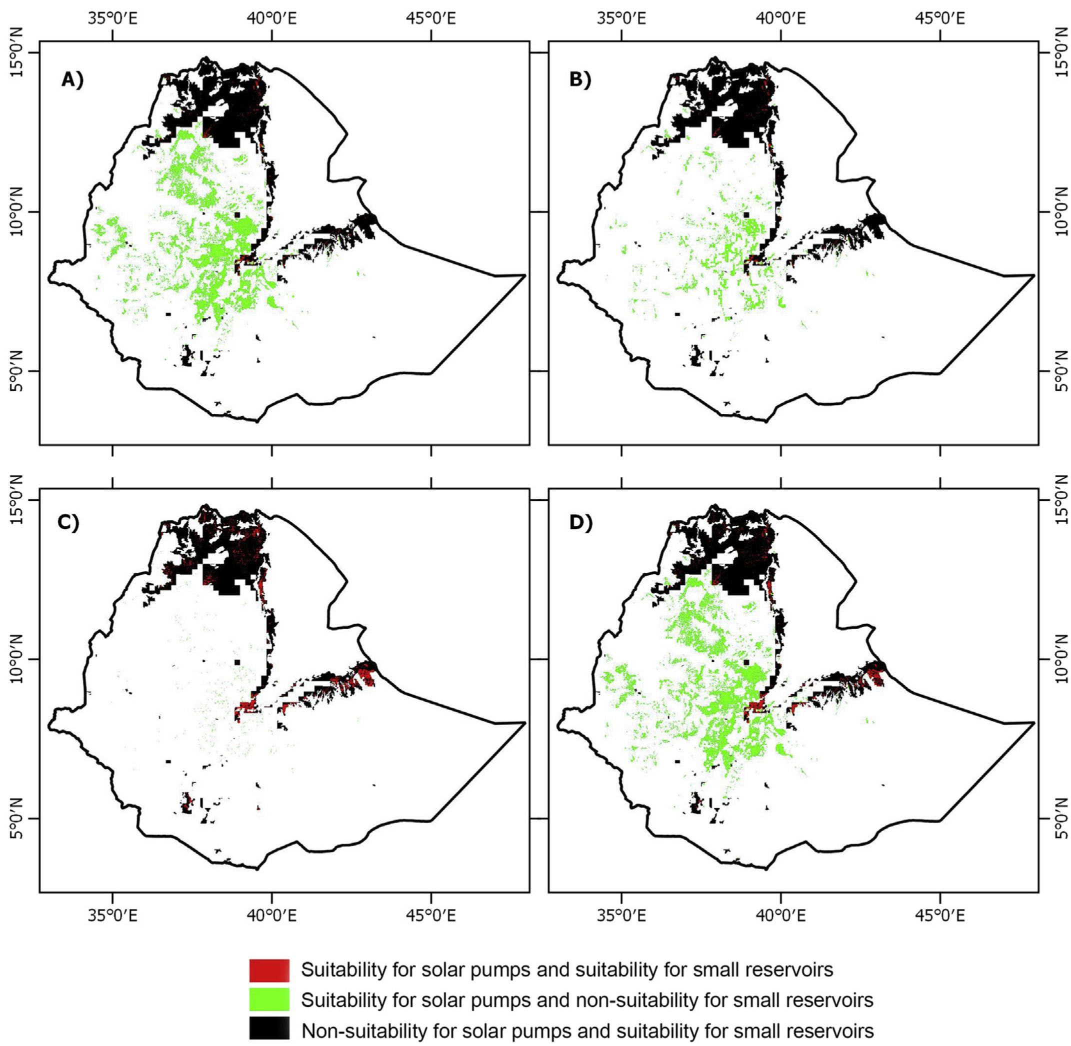

Fig. 8. Comparison of the solar suitability scenarios against the suitable area identified for small reservoirs.
(source: FAO 2012). A) Scenario 1, B) Scenario 2, C) Scenario 3, D) Scenario 4a, and E) Scenario 4b.

(2018) has developed a business model concept for solar PV which provides an economic viability analysis of solar PV-based pumps to reach smallholder farming businesses and irrigation developers. To make solar PV a feasible alternative, there must be access to credit options to purchase technologies, input and output markets, and information on the technology and related on-farm water management practices. The economic analysis for solar PV pump type I in combination with drip irrigation for carrots and other high-value vegetables to significantly decrease labor costs suggests a total value of production of USD 7,115 ha^{-1} (Otoo et al., 2018). This is nearly double the value estimated for the production of high-value vegetables using motorized pump technologies at USD 3,785 ha^{-1} (Gebregziabher, Hagos, Lefore, Haileslassie, & Barron, 2017). Motor pumps have several conditional factors, many of which are similar to solar pumps, though one major benefit to solar pump irrigators in terms of profitability is the reduction in labor associated with solar pump irrigation compared to motor pumps.

The question emerges as to whether small-scale farmers should directly invest in solar PV pumps or whether solar-based rural electrification and off-grid solutions could drive the expansion of irrigation. PV plays an important role in rural electrification, providing off-grid solutions in Africa (Szabó, Bódis, Huld, & Moner-Girona, 2011, 2013). Dagnachew et al. (2017) estimated that 65% of the newly electrified population in SSA could be reached through off-grid solutions, though requiring an investment of USD 22 billion in the period 2010–2030. However, infrastructure development would still be required to transmit to dispersed and often non-contiguous farm plots.

Intensifying agricultural production could improve on-farm income. Results of this study show that, in Ethiopia, solar PV pumps could be used to build resilience in rainfed land covering around 6,642 10^3 ha. In those areas, farmers could either use supplementary irrigation during the short rainfall season or at late onset of the main rainfall season. Moreover, solar PV pumps could mitigate low agricultural productivity due to the occurrence of dry spells within the main rainy season (Vörösmarty et al., 2005). Aside from supplementary irrigation benefits in both the short and main rainfall seasons, the availability of groundwater and surface water resources would allow for additional cropping in the dry season. The implications for SSA could be substantial in terms of keeping much needed pace with consumer food demand and population growth (e.g. van Ittersum et al., 2016).

Large potential for solar PV-based irrigation in Ethiopia was revealed when considering shallow groundwater up to 25 m (Scenarios 1, 2, 4 a and 4b). Studies have shown that despite the current potential of groundwater in SSA (Altchenko & Villholth, 2015), climate change will likely increase water scarcity for the majority of the population (Arnell et al., 2016; Villholth, Tøttrup, Stendel, & Maherry, 2013). Hence, sustainable irrigation and solar PV implementation should be combined with efficient on-farm water management technologies. For example, the combination of solar-powered lifting technologies with drip could sustainably boost agricultural production in SSA (Burney et al., 2010). The combination of solar-based lifting and drip would also reduce labor

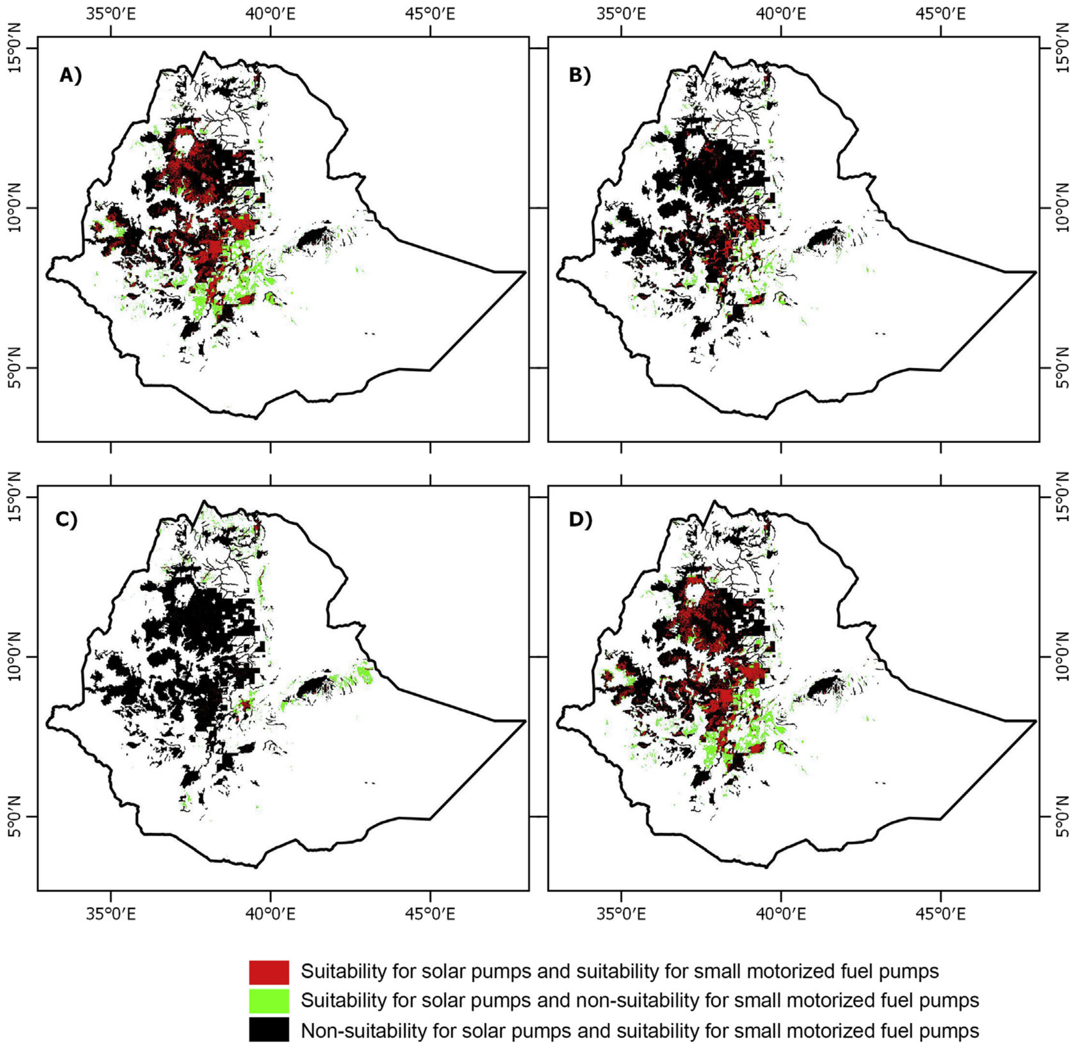

Fig. 9. Comparison of the solar suitability scenarios against the identified suitable area for small motorized fuel pumps. (source: FAO, 2012). A) Scenario 1, B) Scenario 2, C) Scenario 3, D) Scenario 4a, and E) Scenario 4b.

in irrigation as water lifting and application frequently make up the largest costs in smallholder irrigated agriculture (Schmitter et al., 2016, p. 62).

5. Conclusion and recommendations

The study showed a large potential for solar PV-based irrigation in Ethiopia that would enable smallholder farmers to improve resilience with a climate-smart technology. The suitable areal coverage highly depended on the available water resources. Ensuring environmentally sound sustainable expansion of solar-based irrigation requires higher resolution information on groundwater and surface water resources. Evaluating the weighting factors used in this framework showed the importance of including proxies for market access. Market development will be crucial in realizing the solar-based irrigation potential, particularly targeting smallholder farmers with feasible and profitable investments in the technologies. The suitability mapping can provide a needed input to support planning and sustainable implementation of solar-based irrigation, which offers broad social and economic benefits. Solar-based irrigation reduces on-farm irrigation labor when combined with efficient application systems and provides off-grid energy solutions. Solar-based PV pumps can also be used for multiple purposes, including irrigation, livestock watering, and domestic uses, making it a preferred water-lifting technology for women farmers (Nigussie, Lefore, Schmitter, & Nicol, 2017). Hence, solar PV-based solutions should be developed where suitable considering holistic and multi-purpose goals embedded in the right socio-economic context.

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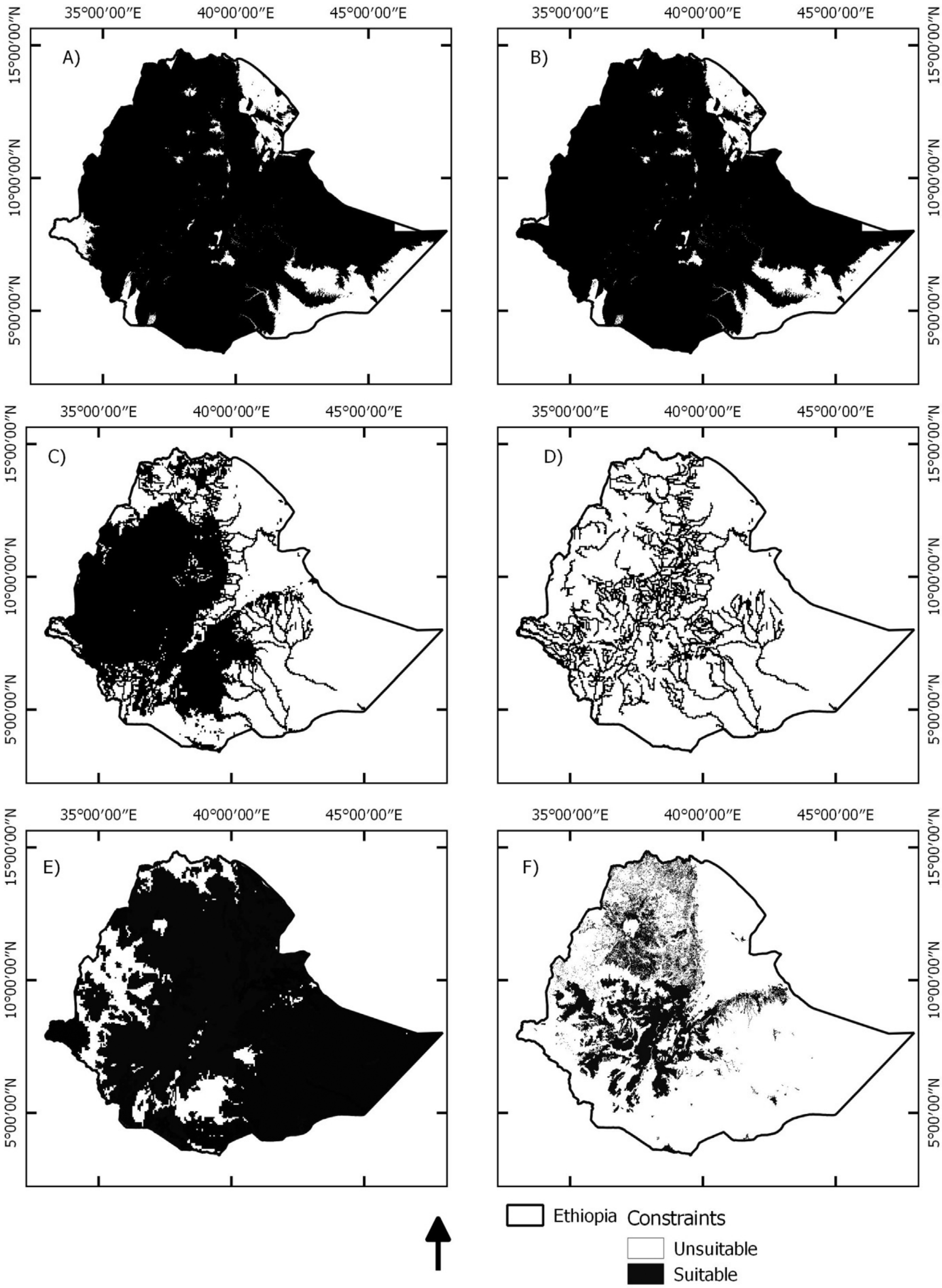
Appendix A

Supplementary Figure S1: Individual constraint maps: A) elevation; B) agro-ecology (based on rainfall and elevation constraints); C) depth to groundwater (0–7 m and 7.1–25 m); D) depth to groundwater (0–7 m); E) groundwater storage; F) land use and land cover; G) town; H) slope; I) soil depth; and J) protected areas.



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